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Sustainability of remote communities: 100% renewable island of Hvar

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Island communities require in-detail mapping of resources available for exploitation for energy purposes, since infrastructure and connections to the mainland present, in most cases, a weak point of the island energy supply. As the present energy supply on Croatian islands relies mostly on fossil fuels and electricity from the mainland, it becomes obvious that exploitation of renewable energy sources is the only solution that leads towards self-sufficiency and sustainable development. In order to design a self-sufficient and sustainable island, three major technological changes are needed: integration of renewable energy sources alongside with energy savings and improvements in energy efficiency in the energy production. Analyses for several other Croatian islands have been performed using Renewislands/ADEG methodology in order to assess all possible outcomes. The scenarios in these cases have shown that islands can become self-sufficient through combining renewable technologies and energy storage systems. Energy storage systems will be crucial for achieving desired objectives in terms of energy independence from the mainland and in general import of fossil fuels. The analysis conducted for the island of Hvar will result in creation of several scenarios which will clearly point out the favorable solutions for improvement of both security of energy supply and covering the majority of energy demand with renewable energy sources and storage technologies. Also, when talking about implementation of renewable technologies on island of Hvar, an optimal mix of technologies must be applied in order to avoid excess costs and to achieve minimal impact on environment in terms of visual pollution.
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I. INTRODUCTION

Since islands are rather specific in terms of behavioral, environmental, and economic conditions, scenarios should propose and investigate the most suitable opportunities for achieving self-sufficiency and sustainability. In order to design a self-sufficient and sustainable island, three major technological changes are needed: integration of renewable energy sources alongside with energy savings and energy efficiency improvements in the energy production.[1] Considering specific island conditions, in order to reduce the mainland dependency, renewable energy sources must be applied in combination with the most appropriate energy storage solutions.[2,3] In such case, energy infrastructure, including grid and energy production facilities should use advanced energy management techniques.[4] Future developments in energy cannot even be imagined without implementation of smart grids, no matter how far that future might seem.[5] Intermittency of solar and wind energy production provides great possibilities for implementation of smart grids which provide greater flexibility in balancing supply and demand.[6]

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Analyses for the self-sufficient and sustainable energy systems have been conducted in many studies[7] and the conclusion is that the development of such systems with existing technology is possible and "*it is not a matter of technology, but rather a matter of making the right choices today to shape tomorrow*."[8] In order to achieve self-sufficient and sustainable energy systems, all sectors need to be considered when integrating large penetration of renewables.[9] Analysis for self-sufficient and renewable energy systems which are based on integration of electric, heat and transport sectors with renewables and water supply are already conducted for the islands of Mljet,[10] Sao Vicente,[2] Porto Santo Island,[11] and Malta.[12] Studies for other islands such as the Island of Dia (Cretan Sea),[13] Aegean Islands,[14] Salina Island (Aeolian Islands),[15] Canary Islands,[16] and Reunion Island[17] have also examined the influence of renewable energy sources on the island system. The importance of examining island systems is directly related to performing the same examination for larger scale systems, e.g., countries such as Denmark,[18] Portugal,[19] Croatia,[20] Macedonia.[21]

One of the requirements for preparing scenarios for island of Hvar is definitely the possibility to choose from variety of technologies and their relations when talking about grid connected systems. The intention to prepare island communities for self-sufficient governing must include stand-alone systems aiming at cost-effective and long-term solutions where infrastructural costs, such as new grid connections, would be unacceptable. Island of Hvar, with a total energy demand of 312 TJ, is a major consumer in the Dalmatian area, especially during the touristic season when the population almost triples.[22] Favorable climate conditions coincide with peak energy consumption, providing an opportunity for peak curtailment during touristic season. The problem of relatively high heating costs, despite the warm climate, is caused by the fact that 22% of total energy demand on the island is obtained from fossil fuels whose price level constantly increases. Fortunately, a large part of heating energy is covered through biomass exploitation (25%), however it is highly doubtable that exploitation of such amounts of biomass on the island can be treated as sustainable. Electricity contributes in total energy demand with 53% which presents a big problem since the island has no electricity production facilities which could meet the demand. Abundant solar resource on island of Hvar is definitely an opportunity for development of local energy production but the single resource is not sufficient due to its intermittent nature. Wind has the same problem of intermittency so the most appropriate and cost-effective solution lies in balancing both solar and wind technologies. When thinking of possible and applicable solutions for island of Hvar, one has limited options to create an optimal mix of technologies which could improve the security of supply (both electricity and heat supply) with incorporation of intermittent renewables.

Analysis in case of island of Hvar will result in creation of several scenarios which will clearly point out the favorable solutions for improvement of both security of energy supply and covering the majority of energy demand with renewable energy sources and energy storage. Resource mapping, therefore, plays a significant role in discovering the appropriate solutions for solving the issues the community population is well aware of.

II. METHODOLOGY

The approach considered in this paper is based on statistical data obtained from the Croatian Bureau of Statistics and data collected by the Energy Institute Hrvoje Požar. Obtained energy data, previously separated according to fuels and consumption sectors, has been prepared for usage in simulating software by determining distribution of hourly values of each energy source (electricity, fuel oil, biomass, and liquefied petroleum gas (LPG)). Climate data taken into consideration has been obtained through METEONORM software to generate results.[23] Before using obtained climate data, each dataset had to be adapted to meet the requirements of the energy system modeling software. The climate data was also used for distribution of heating and cooling energy hourly values throughout the year by applying heating and cooling degree days split also into hourly values. To obtain a comprehensive analysis of island of Hvar energy consumption, in referent year as well as in future modeled periods, certain sections in the total energy consumption had to be calculated separately before actual application in ENERGYPLAN software, e.g., transport sector and building sector.

A. Energy plan model

In order to create a simulation of Island of Hvar energy system, EnergyPLAN model[24] shown in Fig. 1 has been used. It is an input/output computer model that creates an annual analysis in steps of 1 h. The necessary input data are electricity demand; fuel consumption; installed capacities; technology and fuel costs; distribution of wind and solar radiation; and the energy demand in industry, buildings, and transport.

Typical output data include electricity generation, CO_2 emissions and annual cost. As presented in the figure above on the left side, it is visible that ENERGYPLAN software incorporates renewable technologies for both electricity and heat production. The right side of the schematic represents the necessary inputs that have to be placed in order to balance the entire system. The middle part of the schematic represents various conversion technologies, including all relevant components for examining, e.g., an island energy system. Since an island system requires a certain amount of flexibility, it is necessary to incorporate methods of energy storage, as it is made available in ENERGYPLAN software. Prior to using the tool itself, one must prepare the necessary datasets and input energy data that will be used for calculations. Having this said, it is clear that ENERGYPLAN would be the most appropriate solution for determining future energy balance outcomes for island of Hvar. Also, it was previously shown in the case of island of Mljet[25] that ENERGYPLAN provides sufficient options and methods to incorporate all factors relevant for a calculation of an island energy system and for examination of effects of various technologies on an energy system. In general, it can be said that EnergyPLAN model is specialized for large scale integration of renewable energy sources in energy systems and resulting environmental and economic aspects of the integration.[26–29]

The optimization of the most appropriate mix of photovoltaics (PV) and wind turbines in the island system was done by using ENERGYPLAN. At first, it has been considered that all electricity is produced from wind turbines. The capacities of the wind turbines have been reduced gradually and the capacity of the PV increased at the same time to comply with the requirement of achieving 100% electricity from Renewable Energy Sources (RES). The point of optimal wind and photovoltaic energy mix was chosen based on the criterion of the smallest energy storage capacity needed for covering the total energy consumption.

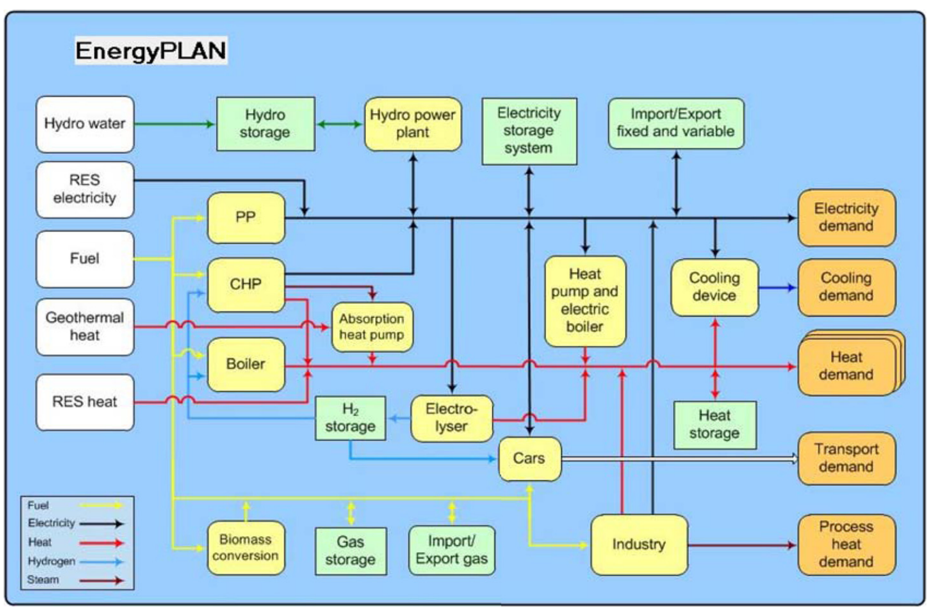

FIG. 1. The structure of EnergyPLAN model.[24]

B. Sector energy demand model

The transport sector incorporates energy demand of both road transport and sea transport to assess the future needs of implementation of new transportation technologies. Road transport is modeled according to demographic conditions taking into consideration the touristic period during summer when the population on the island often doubles or even triples. Also, variation in number of tourists has been included thus predicting changes in energy consumption due to temporary increase in population during the touristic season. Exact number of vehicles is calculated according to statistical data obtained from the Croatian Bureau of Statistics. Vehicles have been divided into groups according to size of vehicle, e.g., motorcycles, cars, vans, etc., and according to fuel type where Electric Vehicles (EVs) will play a significant role in future periods. Improvement of each vehicle technology is incorporated in the calculation through technology efficiencies which are subject to linear increase in considered time span. Technology efficiencies influence the specific energy consumption of each technology. Upon obtaining all necessary information, the energy demand of the road transport is calculated according to

$$E_{TR} = E_{TR,per} + E_{TR,tour}, \tag{1}$$

where E_{TR} represents the total energy demand of the road transport (kWh), $E_{TR,per}$ represents the energy demand of road transportation of permanent population (kWh), and $E_{TR,tour}$ represents the energy demand of road transportation of tourists (kWh). The energy demand of road transportation of both permanent population and tourists is calculated according to

$$E_{TR,x} = E_{SP,TYPE} \times D \times N_{VEH,TYPE}, \tag{2}$$

where $E_{SP,TYPE}$ represents the specific energy consumption of each vehicle technology (kWh/km), D represents annual traveled distance (km), and $N_{VEH,TYPE}$ represents the number of vehicles of each vehicle technology (-).

The building sector has been modeled according to obtained consumption data while taking into account the influence of population and average area per capita of both residential and touristic buildings. Total final energy consumption for heating has been calculated according to

$$E_{F,HEAT} = A_{RES} \times N_{POP} \times e_{av,m^2}, \tag{3}$$

where $E_{F,HEAT}$ represents the total final energy consumption for heating (kWh), A_{RES} represents residential area for heating (m^2), N_{POP} represents total population in taken period (-), and e_{av,m^2} represents the average energy consumption per unit of area (kWh/m^2), which has been calculated for the referent year and then, according to energy efficiency requirements, modeled in the future periods. Energy efficiency measures have been applied through a decrease in heating energy demand, aiming to achieve the low energy standard in 2018 and passive house standard in 2020 with significant implementation of solar thermal technologies.[30] Energy for cooling has been appropriately distributed according to obtained data for the referent year and considered touristic and residential area per capita. Energy for cooling also decreases according to the set up measures. Electricity is assumed with a reduced amount also by considering implementation of energy efficient devices.

III. CASE STUDY ISLAND OF HVAR

A. Island of Hvar—Population, geographical features, and resources

Island of Hvar is located approximately 40 km off the Dalmatian coast and administratively belongs to the Split-Dalmatia County. The island is approximately 72 km long and at the widest part it measures approximately 10 km. Total area of the island amounts to 299 km^2 which makes it the fourth largest island on the Croatian coast. With mild winters where the outside air temperatures rarely falls below 0 °C, the island community can compensate energy needed for heating with energy from biomass and through application of solar thermal solutions for space heating. The average temperature in the coldest winter month is around 8.4 °C and the average temperature in the hottest summer month around 29 °C with daily maximums reaching almost 40 °C.

The permanent population on island of Hvar is around 11 000 with high seasonal touristic changes. The island population almost triples and can be around 35 000 in the peak of the touristic season. The island is connected to the mainland grid with an underwater cable and water supply grid and is very dependent on the import from mainland. High peak consumption can be expected especially in summer touristic season when a lot of cooling devices are plugged in.

B. Scenarios

The first scenario considers "Business as usual" (BAU) activities and does not significantly reduce energy consumption. This scenario is considered in such a way so that it does not follow the EU trends regarding energy efficiency measures and renewables implementation. Also, energy efficiency measures in electricity devices for cooling and general application have not been considered in a significant manner; therefore, it is expected that the total energy consumption will increase throughout the years. Transport sector still relies mostly on fossil fuels; low penetration of electric vehicles is considered. "Business as usual" scenario considers very low penetration of renewable energy sources up to 2030 in order to show the possible outcome of such community management. Also, a scenario BAU-RES, similar to BAU scenario, has been created with the difference of higher renewable energy sources penetration in order to show that energy self-sufficiency and sustainable development is impossible to reach with only implementation of renewable energy sources and lack of energy efficiency measures.

RES scenarios (Sc1, Sc2, and Sc3) have energy efficiency measures and renewables included in previously modeled energy demand, including electricity, energy for heating, and energy for cooling, as well as energy for transport. Apart from meeting the requirement of 100% electricity from renewable energy sources, all three scenarios (Sc1, Sc2, and Sc3) must also meet the requirement of 100% of total energy demand from renewable energy sources in the year 2030.

Scenario Sc1 has been used to examine the influence of electricity production from photovoltaics and to determine the necessary size of the system that would cover island electricity consumption. It is expected that a significant size of the energy storage, preferably pumped hydro storage, will be necessary to cover the electricity demand in 2030, despite reduced energy consumption.

The second scenario, Sc2, has been used to determine the influence of extremely intermittent wind power on the isolated island system. However, it is expected that the size of the energy storage will be smaller than in the first scenario.

The third scenario, Sc3 has been used to determine the optimal mix of photovoltaics and wind turbines with energy storage. It has been envisaged that photovoltaics will cover the majority of daily energy demand and wind turbines a part of the energy demand during the night.

The final energy consumption for five scenarios has been presented in Fig. 2.

IV. RESULTS AND DISCUSSION

All five scenarios were calculated with ENERGYPLAN tool in order to compare the results and find the optimal solution for energy supply of island of Hvar. The results have shown that energy efficiency measures are needed in order to achieve a 100% renewable community. Scenarios BAU and BAU-RES have yielded results that show unfavorable outcomes for the island community in terms of fuel dependency on the mainland. BAU scenario where significantly smaller implementation of renewable energy sources is envisaged is especially unfavorable since the consumption of fossil fuels hasn't been decreased and the electricity supply still in majority depends on the mainland.

BAU-RES scenario shows some progress in terms of electricity supply from renewable energy sources; however, the energy supply is still highly dependent on mainland and fossil fuels. If managed like this, the community will not reach self-sufficiency and exploit the

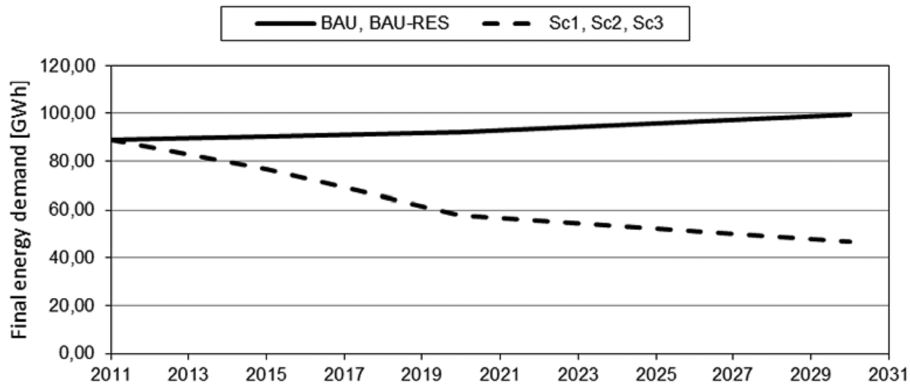

FIG. 2. Final energy consumption in modeled scenarios.

potential of available resources on the island. It has been shown already in BAU-RES scenario that the optimal mix of photovoltaics and wind turbines could cover the majority of electricity demand of the island, despite the increase in electricity consumption. Also, due to excess electricity production in BAU-RES scenario, a storage solution must be implemented in order to avoid exporting the produced electricity. However, in comparison with RES scenarios (Sc1, Sc2, and Sc3), the installed power of both photovoltaics and wind turbines would have to be significantly higher to cover the whole electricity demand as modeled. Results in scenarios Sc1, Sc2, and Sc3 have yielded satisfactory results depending on the RES technology applied.

The scenario Sc1 with photovoltaics as the only electricity producer on the island needs a large photovoltaic power plant of almost 38 MW in order to cover the electricity supply in combination with energy storage solution. The implementation of such large system would require a large area on the island covering both usable and unusable parts of the island. Evidently, this type of solution will require a large storage since the electricity production is available only during the daytime and the electricity demand must be covered also during the night. Nevertheless, it has been proven that the total electricity demand (with implementation of energy efficiency solutions and energy efficient devices) can be covered with a large photovoltaic system.

Scenario Sc2 considers implementation of only wind turbines to cover the total electricity demand. When examining the results, it is evident that the power of the wind turbine system is more than two times smaller than the photovoltaics system considered in scenario Sc1. However, due to intermittency, the necessary storage capacity approximately corresponds in both

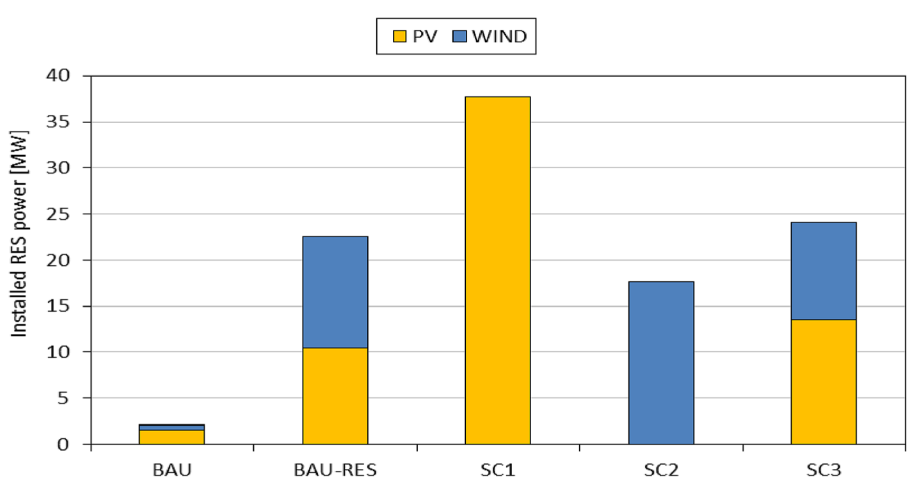

FIG. 3. Installed RES power in 2030.

TABLE I. Results of the scenarios.

Scenario	Year	Installed wind power (kW)	Installed PV (kW)	Installed storage capacity (GWh)
BAU	2015	0	100	0
	2020	50	500	0
	2025	300	1000	0
	2030	500	1500	0
BAU-RES	2015	2000	1500	0.001
	2020	4000	3000	0.015
	2025	9000	7000	0.559
	2030	12 000	10 500	2.580
Sc1	2015	0	2500	0
	2020	0	6000	0.008
	2025	0	20 000	0.106
	2030	0	37 706	7.337
Sc2	2015	2500	0	0
	2020	8000	0	0.171
	2025	13 000	0	1.432
	2030	17 641	0	7.354
Sc3	2015	1000	1000	0.005
	2020	2500	3000	0.005
	2025	8000	7000	0.240
	2030	10 500	13 562	4.028

cases pointing out that implementation of one RES electricity production technology is not the appropriate solution.

Scenario Sc3 has been prepared in such manner so that total electricity demand in 2030 is covered by implementation of both photovoltaics and wind turbines aiming to achieve the energy storage capacity as small as possible.

Installed capacities of the power plants for all five scenarios in the year 2030 are presented in Fig. 3.

Installed capacities of the power plants for all five scenarios for the years until 2030 are presented in Table I.

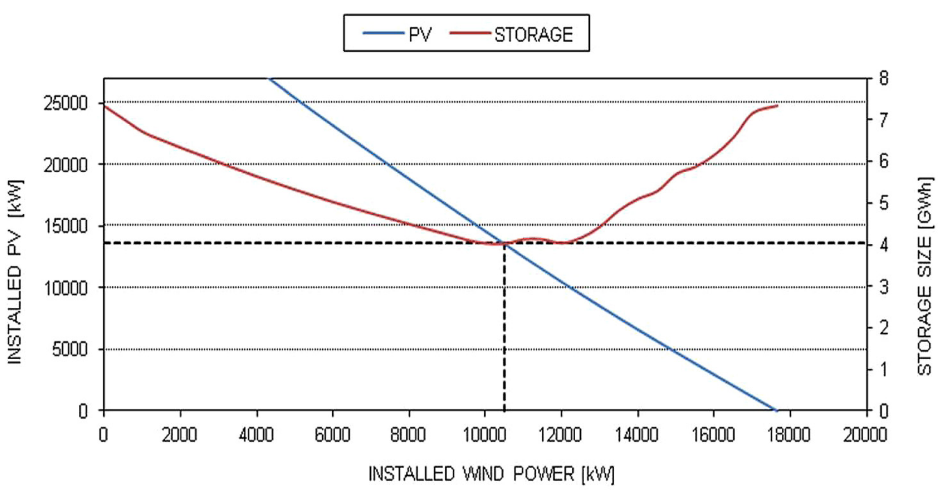

FIG. 4. Optimal capacity of wind turbines and photovoltaics.

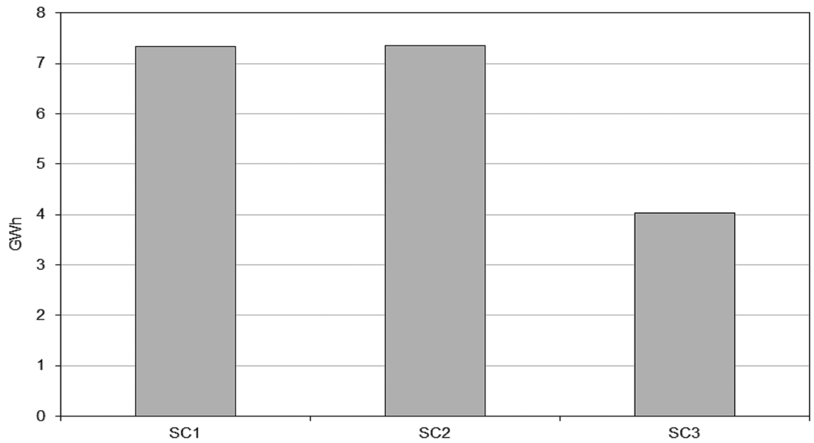

FIG. 5. Size of storage needed for implementation of considered amounts of RES in 2030.

The examination of optimal system size ratios between photovoltaics and wind turbines did not include capital and operation costs optimization,[31] but only a technical analysis[32] for optimizing photovoltaics and wind systems size while avoiding the critical excess energy production with energy storage. The size of the photovoltaic system must be able to provide sufficient energy for covering the energy demand during summer peaks when the wind turbines do not produce much energy. Also, the balance must be achieved in winter periods when the photovoltaic system has relatively low production and wind turbines must compensate with electricity production. The energy system on the island should also be optimized in order to reduce the environmental impact and visual pollution and to reduce the land occupied by energy systems.

As presented in Fig. 4, the optimal solution for island of Hvar, with energy demand according to scenarios Sc1, Sc2 and Sc3, would be the implementation of 10.5 MW of wind turbines and 13.5 MW of photovoltaics. The necessary energy storage for produced excess electricity would have to be able to accumulate 4 GWh. The critical period for electricity production is mostly in the spring period where consumption of electricity for heating significantly decreases and the cooling demand is not yet that large to consume significant amounts of electricity. In case of Sc3, the size of energy storage is approximately 45% smaller than in cases of Sc1 and Sc2 thus proving that the optimal mix of renewable would provide a stable island electricity supply with consuming less area of the island (Fig. 5).

The main reason behind preparing an analysis with energy storage in the islands' energy system was to eliminate critical excess electricity production and export to the mainland. The intention is to cover all energy needs of the island community with locally available renewable energy sources. The comparison of the necessary storage size was done only for 100% renewable scenarios—Sc1, Sc2, and Sc3.

V. CONCLUSION

Island communities have always struggled towards autonomy and independence from the mainland and renewable energy sources have given them the opportunity to achieve the desired goal. Of course, prior to trying to achieve autonomy and independence, comprehensive resource analysis must be conducted in order to assess the scope of work to be done. The Island of Hvar has sufficient renewable resources to achieve 100% renewable system through implementation of energy efficiency measures, energy efficient devices, and renewable energy sources. The technical analysis (without taking costs into consideration) made in this paper has shown that the complete projected energy demand of approximately 47 GWh in 2030 can be covered with a mix of renewable energy sources in combination with energy storage of approximately 4 GWh capacity. The examined scenarios have pointed out that the Island of Hvar can achieve self-sufficiency with locally available resources and by following the EU defined goals related to energy efficiency and renewable energy sources.

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